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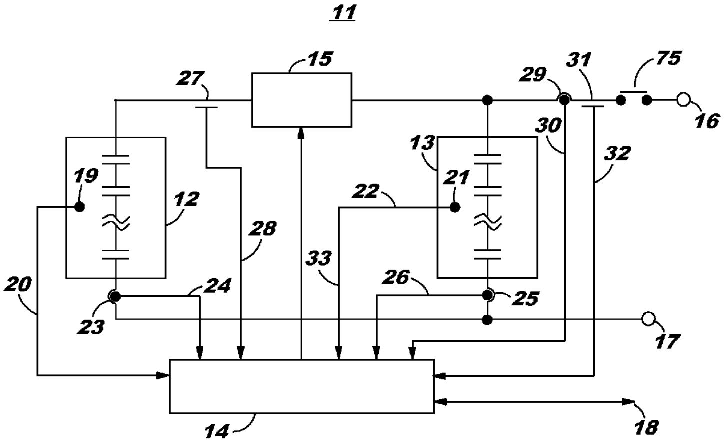
(54) Title: BATTERY SELF-WARMING

FIG. 1



(57) Abstract: The problem that a battery will have reduced function (both in ability to deliver energy and in ability to receive energy for storage) as a function of low temperature is addressed by cycling current out of the battery and into a capacitor, and from the capacitor back into the battery, all at sub-hertz frequencies. This warms the battery due to its own internal resistance, thereby warming the battery. The warmth is delivered exactly where it is needed. The currents can be smaller at first (when the battery's current-delivery abilities are limited due to cold) and can be larger as the battery warms up, until the battery is warm enough to deliver most of its capability. Such cycling of current can provide warming that is useful in cold terrestrial environments or in space.

Battery self-warming

Background

Batteries don't work well when they are cold. Many approaches have been attempted for overcoming the problem that a battery doesn't work well when it is cold, including trying to warm up the battery or trying to design the battery so that it works well despite being cold. Some of these approaches do not work well, or are expensive, or make things heavier then they would otherwise be.

The problem that batteries don't work well when they are cold is evident when one is using equipment that is powered from the battery, for example if a car won't start in cold weather. But the development and growth in popularity of so-called “hybrid” cars (cars in which regenerative braking is employed and the derived energy is stored in a rechargeable battery) emphasizes a distinct problem, which is that when the battery is cold it cannot be charged very well, meaning that it cannot store energy from regenerative braking.

The problems that batteries don't work well when they are cold present themselves in cold weather (for example cars, construction equipment, military, and aerospace). Such problems also present themselves in space, for example in satellites.

The problem referred to here is, of course, actually a constellation of problems, a function not only of ambient temperature but also of other factors such as battery chemistry (lead-acid, lithium-ion, nickel-metal-hydride) and of the state of charge of the battery. (A discharged lead-acid battery, for example, freezes at a different temperature than a fully charged lead-acid battery, which provides a vivid reminder that the state of charge can make a big difference.)

With advanced chemistry batteries such as lithium-ion and nickel metal hydride the stored energy is simply not accessible in cold climates. The energy is there but can only be removed at very low rates, on the order of C/5 and lower. A good example of this is certain hybrid automobiles that are known to have virtually no recuperation capability when cold so that the driver will not benefit from energy recuperation for at least the first seven miles of driving in cold. For even larger battery packs the situation becomes far worse because of high thermal time constants of the battery pack.

Many approaches have been attempted over the years to overcome this problem. This problem represents a long-felt need, until now not satisfactorily solved.

One approach is to make the battery arbitrarily large. If, for example, the temperature gives rise to a loss of all but one-fourth of the battery function, then one approach is to make the battery four times as large. While this approach is sometimes workable in fixed-location applications such as cellular communications huts, it is of no help with vehicles or satellites.

Another approach is to attempt to heat the battery. Such heating will probably not warm the battery uniformly and can then risk damage to a particular cell of the battery if the cell is cooler than the other cells (and fails thereby due to exceeding its limits) or if a particular cell is hotter than the other cells (and fails thereby due to over-temp effects). In some applications it will not be at all clear where the energy can be gotten to carry out the heating. Adding an external battery heater adds weight and takes up space, and sometimes this is undesirable. The energy spent on heating will not all reach the battery if such an approach is attempted, because some of the heat will go in other directions.

A publication called R. Carlson, D. Bocci, M. Duoba, “On-Road Evaluation of Advanced Hybrid Electric Vehicles over a Wide Range of Ambient Temperatures,” Argonne National Laboratory Advanced Powertrain Research Facility, July 2007 helps to show that the present needs have been known for some time. Yet suitable approaches for addressing these needs have not until now been found. Pages 18-19 of this publication show actual test results and provide comments on HEV performance at cold testing. The lack of battery power at cold temperature means that HEV function is not present below 0 degrees Celsius.

Prior-art attempts to provide battery warming include JP 2008 035581 A to Toyota Motor Corp. (14 February 2008), US 6072301 A to Ashtiani et al. (6 June 2000), and US 5990661 A to Ashtiani et al. (23 November 1999).

US 6072301 A proposes an inductor together with a film type capacitor as a resonant circuit serving as the source of circulating high frequency (i.e., 25 kHz) current through the battery to effect self heating. Subsequent experience has shown, however, that exposing the battery to 25kHz current at any significant amplitude causes damage to the battery.

US 5990661 A proposes injecting high frequency current to self heat a battery by warming the electrolyte because of internal power dissipation within the electrolyte. That the current is at a high frequency is understood when one considers that the inductor mentioned in the patent has a physical size that is (necessarily) proportional to 1/f. If one were to attempt to employ the circuitry of the patent at, say, one-tenth of the nominal frequency of 25 kHz, this would be 2.5 kHz. But this would require that the inductor be ten times larger than originally contemplated. If one were to attempt to employ the circuitry of the patent at a sub-Hertz frequency, the inductor would probably weigh almost as much as the automobile itself. It will thus be appreciated that the current flows proposed by this document are indeed at a high frequency.

Such an approach (injection of HF currents into a battery) was perhaps not recognized at the time as being detrimental to the battery. Subsequent experience, however, has shown that such a heating approach gives rise to electrode exfoliation and electrolyte breakdown by high frequency friction. Accelerated aging of the electrode-electrolyte is a consequence. Neither of these high frequency approaches has been placed into actual use with actual commercial products, presumably due in part to the gradual appreciation that it can age the battery.

JP 2008 035581 A describes a power supply used to quickly raise the temperature of a hybrid vehicle battery pack. In its approach Toyota recommends using a relay to switch a resistor across the pack to generate heat to warm the cells. Toyota's system comprises a DC-DC power converter to interface the NiMH battery to the traction drive electronics. Toyota takes every precaution to minimize high frequency ripple current exposure to the battery by designing the DC-link on this electronics to have at least three different electrolytic and film capacitor filtering elements so that high frequency ripple current leakage to the battery is minimized. This may be taken as an indication of the gradual appreciation within the relevant art that it is better to avoid passing high frequency current through the battery. It will be appreciated that the I^2R heat developed in the resistor will not all go into the battery, and the heat that does go into the battery will heat some parts of the battery more than other parts.

It would thus be very desirable if an approach could be devised which would permit keeping a battery warm enough to carry out its functions, so that it could (for example) receive regenerative-braking energy from the outset of vehicle operation rather than having to wait for the vehicle to warm up. It would be desirable if such an approach could be gotten without adding weight to the equipment, and without having to take up space for added equipment. It would be desirable if such an approach could be obtained without having to add physical complexity to the system beyond whatever is already there to serve existing functions. More subtly, but perhaps more importantly, it would be very desirable if the warming activity could be more nearly targeted to the location of the need, thereby minimizing the problem of heat going in directions that don't help.

Summary of the invention

The problem that a battery will have reduced function (both in ability to deliver energy and in ability to receive energy for storage) as a function of low temperature is addressed by cycling current out of the battery and into a capacitor, and from the capacitor back into the battery. The cycle time is on the order of seconds or tens of seconds. This warms the battery due to its own internal resistance, thereby warming the battery. The warmth is delivered exactly where it is needed. The currents can be smaller at first (when the battery's current-delivery abilities are limited due to cold) and can be larger as the battery warms up, until the battery is warm enough to deliver most of its capability. Such cycling of current can provide warming that is useful in cold terrestrial environments or in space.

Description of the drawing

The invention will be described with respect to a drawing in several figures, of which:

- Fig. 1 is a functional block diagram of an exemplary hybrid battery architecture including a converter 15 and controller 14;
- Fig. 2 shows current cycling according to the invention;
- Fig. 3 portrays a typical energy availability as a function of ambient temperature and of various levels of current cycling;
- Fig. 4 portrays a typical comparison of resistivity of electrolyte in a battery and in an ultracapacitor;
- Fig. 5 shows the converter 15 in greater detail;
- Fig. 6 shows the controller 14 in greater detail; and
- Fig. 7 is a functional block diagram of an exemplary hybrid automobile.

Detailed description

Some further background may help in explaining how particular circuit elements may be selected for use in connection with the invention.

A general term can be defined, namely "electro-chemical energy storage". This can be divided into Faradaic and non-Faradaic storage, the former generally meaning storage through redox (reduction and oxidation) reactions, generally batteries, and the latter generally meaning storage through storage of an electrical polarization, generally capacitors. Faradaic storage can be divided into aqueous-electrolyte storage and organic-electrolyte storage; examples of the former including lead-acid and nickel-metal-hydride cells and examples of the latter including lithium-ion cells. Non-Faradaic storage may be divided into symmetric capacitors (ultracapacitors) and asymmetric capacitors (supercapacitors). Each of these categories may in turn be divided into aqueous- and organic-electrolyte storage, examples of the former being sulfuric acid and potassium hydroxide, and examples of the latter being AN/TEATFB and PC/TEATFB and ionic liquid. Ultracapacitors (symmetric carbon-carbon type of electrochemical capacitors) and supercapacitors (asymmetric metal oxide - carbon type of electrochemical capacitor) are thus a sub-class of electrochemical capacitors.

Fig. 1 is a functional block diagram of an exemplary hybrid battery architecture 11. Terminals 16, 17 connect to loads and/or power sources external to the architecture 11. A battery 13 connects to the terminals 16, 17 through current sensor 29 and voltage at the battery 13 is measured by voltage sensor 31. Capacitor 12 is provided, which is preferably an ultracapacitor. Power converter 15 permits controlled passage of power from the battery to the capacitor or from the capacitor to the battery (or not at all) under control of converter duty cycle command line 33. Voltage sensor 27 senses the voltage across the capacitor 12, and current sensor 23 senses current into or out of capacitor 12. Current sensor 25 senses current into or out of battery 13. Temperature sensors 19, 21 sense internal temperature of capacitor 12 and battery 13 respectively. Sense lines 20, 24, 28, 22, 26, 30, 32 provide information from the just-described sensors to an energy management system controller 14. Controller 14 provides a converter modulation signal at the converter duty cycle command line 33. Controller 14 has a bidirectional control/data bus 18 which may be communicatively coupled with circuitry external to the architecture 11.

In Fig. 1 the energy management system controller (EMS) 14 monitors the ultracapacitor temperature, current and voltage (at lines 20, 24, and 28 respectively), the battery temperature, current and voltage (at lines 22, 26, and 32 respectively), and current to and from the load (at line 30). The controller has control inputs from CAN or other communications channel 18, and reports out to the same communications channel 18, and generates the power converter duty cycle command on line 33.

Turning now to Fig. 5, the converter 15 is shown in greater detail. The converter 15 is basically a three-terminal device (not counting control line 33 and a status line 76, the latter omitted for clarity in Fig. 5). A first terminal connects with the ultracapacitor 12, a second terminal connects with the battery 13, and a third terminal is ground. Inside the converter 15 is a half-wave boost-buck bidirectional circuit to be described in more detail. Switches 54, 58 are controlled by control 51 which takes its commands on line 33 as mentioned above in connection with Fig. 1. Switches 54, 58 are paralleled by rectifiers 56, 55 respectively. Inductor 53 and capacitors 52, 57 are also seen.

It will be appreciated that other bidirectional power converter topologies may be employed, such as a full-wave boost-buck converter, a Cúk converter, or a SEPIC/Luo converter. Some of the factors that might affect the choice of particular converter topology are discussed in “Comparing DC-DC Converters for Power Management in Hybrid Electric Vehicles”, R.M. Schupbach, J.C. Balda, Electric Machines and Drives Conference, 2003, IEEE International, Volume 3, pages 1369 - 1374 (2003), which is incorporated herein by reference. Any of several suitable topologies could be employed without departing in any way from the invention.

Fig. 6 shows the controller 14 in greater detail. A microprocessor 67 executes code in ROM or PROM or EPROM 70 and uses RAM 71. A communications bus interface 72 permits the processor 67 to communciate on bus 18 (see Fig. 1). Power (typically 12VDC) is provided at 62 and power supply 68 develops voltages 69 used at various locations within the controller 14. Digital I/O 74 permits the processor 67 to receive status information on line 76 from the power converter 15, and permit the processor 67 to provide discrete outputs 75 such as, for example, annunciation of over-voltage, over-current, or over-temperature conditions, or fault conditions, on an indicator panel visible to the user. The chief control outputs are an output to contactor 75 (via output driver 72) and an output 33, typically pulse-width-modulated, to power converter 15 by means of driver 73.

Inputs to the controller 14 are for example the current at the ultracapacitor on line 24, the current at the battery on line 26, the external current 30, the voltage at the capacitor on line 27, and the voltage at the battery on line 32. These signals, each analog in nature, are multiplexed at 63 and made available to analog-to-digital converter 65 to the processor 67. The current measurements may be made in any of a number of ways without departing from the invention, for example by means of a toroid surrounding the current-carrying conductor, or a leaf-shunt or Hall-effect sensor. The voltage measurements may be made in a number of ways without departing from the invention.

Other inputs to the controller include temperature measurements at the ultracapacitor on line 20 and at the battery on line 22, as well as an ambient-temperature measurement on line 61. These temperature measurements may be performed for example by RTDs or thermocouples or other ways, without departing from the invention. Each such signal is passed to an appropriate analog processing circuit depending on the type of sensor being used (omitted for clarity in Fig. 6) and thence to a multiplexer 64 and to an analog-to-digital converter 66 and thence to the processor 67.

Suitable ESD (electrostatic discharge) protective circuitry is provided at each input or output to reduce the susceptibility of the controller to such harms. Suitable EMI (electromagnetic interference) circuitry is provided to minimize propagation of EMI from the controller to other devices nearby. The ESD and EMI circuitry is omitted for clarity in Fig. 6.

Fig. 7 is a functional block diagram of an exemplary hybrid automobile 71. Wheels 72 are in contact with the ground. Each wheel 72 has a respective electrohydraulic brake 82 with control line 85. One of the goals of course is to employ regenerative braking when possible. Thus when possible, braking is accomplished through appropriate control of motor-generators 74, 75. Such braking converts kinetic energy (from the moving vehicle) to electrical energy which then recharges battery 13 or capacitor 12 or both, via circuitry the details of which are omitted for clarity in Fig. 7. One set of wheels 82 is on axle 81 and is powered by motor-generator 74 and is regeneratively braked by motor-generator 74, mediated by inverter-rectifier 84.

The other set of wheels 82 is on axle 80 which has differential 79 connected with drive shaft 78. Internal combustion engine 73 is coupled with motor-generator 75 and is in turn coupled with torque converter 76 and automatic transmission 77. Inverter-rectifier 83 mediates between motor-generator 75 and the energy storage system 12, 15, 13. Contactor 75 permits isolation between the energy storage system and the inverter-rectifier 83 as needed. Energy storage system 12, 15, 13 is as described above in connection with Fig. 1.

The invention makes use of an active combination of ultracapacitor and battery (of any type) where a power converter is placed in either the ultracapacitor branch (preferred as shown in Fig. 1) or in the battery branch of the actively paralleled system. The idea is that after a prolonged cold soak, for example a plug-in hybrid electric vehicle or battery-EV parked in a driveway or in a parking ramp overnight or for some days will have a battery temperature equilibrated to the ambient, perhaps -20 degrees C.

With a hybridized energy storage system consisting of the battery module, an ultracapacitor module, a bidirectional power converter and energy management system controller it becomes feasible to use the highly efficient ultracapacitor to cycle some of the battery energy in progressively increasing levels to effectively self-heat the battery through internal power dissipation. This is battery self-heating according to a controlled strategy that can overlay the vehicle propulsion power demands on the battery even when the ultracapacitor pack is being used to cycle drive dynamic energy.

Turning back to Fig. 2, what is shown is current cycling according to the invention. In Fig. 2 the action of the EMS 14 is to take some of the battery energy when cold and cycle this at a low rate (low peak power) into the ultracapacitor 12, and then to return this energy to the battery 13, again at a low rate, is shown at the time t_0. The battery 13 self-heats according to the internal power dissipation via its internal resistance and this power level as dictated by the battery pack thermal parameters (R_{th} [K/W] and Cth [J/K]). Continuation of EMS power control for battery self-heating continues at power rates linked to the measured battery temperature at 21 which could be a thermocouple or some other temperature sensing element, such as an RTD. After some time, at t_2, the battery internal temperature has been increased sufficiently for a substantial portion of its stored energy to now become accessible. Therefore, by time t_3 the power recirculation is ramped down, again according to monitored temperature at 21. The cycling is typically on the order of seconds or tens of seconds. In one embodiment the heating will be carried out by means of current passing in one direction for at least one-tenth of a second, and later passing in the other direction for at least one-tenth of a second, and so on. Such cycling is at no greater than five Hertz. It is thought to be preferable, however, to carry out the cycling at sub-Hertz rates, for example with each interface lasting at least half a second. In one embodiment the unidirectional currents persist for some seconds at a time, for example at least two seconds at a time.

It is instructive to consider the level of current together with the time scale for a typical system. In a typical system the ultracapacitor is actually an ultracapacitor bank of 50Wh to 100Wh capacity.

Transferring current between a bank of that size and a suitable battery represents passing very large energy packets back and forth. Given the typical size of an energy packet, then even at relatively high currents (say 50A to 300A), the time required to pass that much energy back and forth amounts to a duration of current flow on the order seconds of transfer time. Thus if we use the term “frequency” to describe this passage of current back and forth, the frequency is typically a sub-Hertz frequency (meaning less than one Hertz). The converter in this energy exchange is simply a pass-through mechanism to regulate the current amplitude as a function of battery temperature.

It will thus be appreciated that what is described here is the use not of high frequency current (as in the cited Ashtiani references above) but instead the use of the high energy of the ultracapacitor (not possible in any of the above patents) to circulate through the battery pack at variable and temperature dependent amplitude so as not to do any damage to the battery but to self heat due to Joule losses in the electrolyte by essentially unidirectional current persisting for seconds (not micro-seconds) thereby heating the cell internally.

Fig. 4 portrays a typical comparison of resistivity of electrolyte in a battery (line 51) and in an ultracapacitor (line 52). The vertical scale is arbitrary units of relative resistivity and the horizontal scale is temperature in Celsius degrees. What can be appreciated from this graph is that at cold temperatures the capacitor worsens only slightly in resistivity, while the battery's resistivity gets much, much worse. At -30C the ultracapacitor resistance increases by 80% over its room temperature value (that is by the factor 1.8x) whereas the advanced chemistry battery resistance (lithium-ion power battery for example) increases by a factor of 15x to 20x over its room-temperature value.

From this graph it might be thought that the best course of action is simply to eliminate the use of a battery altogether, and to use a capacitor exclusively. But this is not a workable choice, because it is important to have a high energy density. And the energy density for a battery is likely (depending on some factors including the choice of battery chemistry) to be ten or twenty times that of an ultracapacitor, and a hundred or a thousand times that of an ordinary capacitor such as a paper or film or tantalum capacitor. This means that nearly all of the energy storage will need to be in a battery.

As will be appreciated, the invention offers its benefit when two electrochemical storage energy devices are available, one of which (broadly speaking) has high energy density and the other of which (broadly speaking) performs well at low temperatures. As a general matter the Faradaic storage approaches do well so far as energy density is concerned but do not do well at low temperatures (see Fig. 4). And as a general matter the non-Faradaic storage approaches do far less well so far as energy density is concerned, but do much better at low temperatures (again see Fig. 4). Thus although the embodiments set forth herein use specific storage types (such as particular types of batteries and ultracapacitors) it will be appreciated that the paired storage devices for use according to the invention could be more broadly chosen.

Returning to Fig. 2, and making the same point in different words, at first the current that is passed back and forth between the battery and the capacitor will need to be a relatively small current because the cold battery cannot tolerate higher currents in or out. As the battery warms up, the current that can be passed in and out can be greater. Eventually the battery is as warm as desired (for example with nearly all of its energy capability available). The controller 14 will limit the current in or out of the battery to a level small enough to be consistent with the energy capability of the battery at a given internal temperature.

It will be noted that if the temperature of the capacitor 12 at 19 is too low (close to the freezing point of the electrolyte within) then the controller 14 will preferably not carry out the current cycling.

It will be noted that if the state-of-charge of the battery 13 is too low (such that the power consumed by the controller 14 and converter 15 risk draining the battery completely) then the temperature cycling will preferably not be carried out.

It will be appreciated, however, that judicious use of the current cycling activity may in fact permit keeping the capacitor 12 safely above the freezing point of its electrolyte, which in turn keeps the capacitor available for use in current cycling for purposes of maintaining a desired level of battery energy availability.

It will also be appreciated that if the user of the equipment is able to predict when battery energy availability will be needed, then this need can be communicated to the controller 14 so that the controller 14 could initiate current cycling “just in time” to make the battery energy available just when needed. In this way the loss of energy to heating activities can be reduced to the minimum amount.

Fig. 3 portrays a typical energy availability as a function of ambient temperature and of various levels of current cycling. The vertical axis shows energy available under particular conditions. By this is meant not only energy available to be delivered to loads (e.g. starter cranking or locomotion) but also the ability to receive energy (e.g. due to regenerative braking). The horizontal axis shows ambient temperatures for example -30 degrees C, or zero degrees C, or 45 degrees C. In the absence of the present invention, the available battery energy capability as a function of temperature is shown with curve t_0. If, however, the internal battery temperature at time t_3 is developed, then the curve t_3 shows the available battery energy capability. Intermediate curves show the battery energy capability at internal battery temperatures developed at intermediate times t_1 and t_2.

What is depicted, then, is the increasing accessible energy of the battery 13 with the passage of time, under the action of the EMS self-heating strategy. As time passes (during the current cycling), the battery 13, through its own internal resistance and the recirculation of power via the ultracapacitor's highly efficient and reciprocal energy transfer, exhibits increasing accessible energy levels at a given internal temperature, for example at an internal temperature of 20 degrees C. This means that the battery 13 can now recuperate some energy and begin to participate with the ultracapacitor as a more functional actively paralleled system. The actively paralleled system effectively implements decoupled power and energy via the EMS at cold ambient temperatures that otherwise would not be possible.

Prior-art systems must rely completely on the battery alone for their function, and there is no real mechanism to recirculate power to bring about battery self-heating. Today a system designer is left to rely on drive-cycle dynamics (drawing power while driving, and regenerating power while driving) to eventually self-heat the battery in a rather crude and uncontrolled way. Especially during the first minutes of operation, typically, energy that might have been stored due to regenerative braking (for example) is instead simply lost and the ability to recuperate available energy is simply absent for those first minutes.

As mentioned briefly above, the teachings and benefits of the invention offer themselves in wide range of consumer, commercial, industrial, military, and aerospace applications. Examples include PHEV (plug-in hybrid electric vehicle) and BEV (battery electric vehicle) and REV (range-extended vehicle) electrified vehicles, and remote power and communications installations needing energy storage that are powered only by renewable sources such as wind and PV (photovoltaic), any of which are in places where the climate can be very cold. The invention offers its benefits as well in military vehicles of all types (including the specific case of military ground vehicle cold cranking aids), in aircraft, and in satellites.

It will be appreciated that the current cycling will no longer work if the ultracapacitor electrolyte freezes (-60 degrees C for one commonly employed ultracapacitor electrolyte). So if the application happens to be in some electronic unit that is subjected to -60 degrees C, then one approach would be to use a different electrolyte (having a lower freezing point) in the ultracapacitor. If the ultracapacitor freezes, then later when the ultracapacitor thaws out, the current cycling could again be employed.

It will be appreciated that the approach of the invention has the advantage that its heating effects within the battery 13 are targeted fairly well to the general location where heat is needed, namely within the battery itself. This avoids lossy heating in which heating energy is lost to locations outside the battery, as would be suffered if heating were done with a heating element located outside the battery. Such heating effects are directed to each cell of the battery, thereby providing heating to each cell. It is hoped that this would reduce anisotropic heating that might happen (if an external heating element were employed) such that one cell might get heated much more or less than some other cell.

The self-heating method is very effective because heating is mainly localized to the battery cell electrolyte by the current cycled between the ultracapacitor and battery. This is efficient because the proportion of battery cell electrolyte resistance to total cell resistance at room temperature is on the order of 65%, but at cold temperature the 1500% or greater increase in cell resistance is due entirely to the electrolyte. Therefore, the battery case temperature may still be cold but full function is available because the electrolyte temperature is raised to its preferred temperature range.

An alternative storage mechanism (for storing energy outside of the battery, to be pumped back into the battery as described herein) is the use of a flywheel. Flywheels are not, however, good choices for mobile applications, since the angular momentum can cause problems. Even in a stationary application, the flywheel takes up space, and has some weight, and adds physical complexity to the system. It represents adding moving parts that might otherwise not be needed. The storage mechanism of the ultracapacitor, by comparison, has the potential advantage of no moving parts and no angular momentum. In many systems the ultracapacitor and power converter would be present anyway (for other reasons unrelated to the need to heat the battery) and so would not add weight or take up space beyond the weight and space that would already have been justified for other reasons.

Those skilled in the art, inspired by and gaining insight from the teachings herein, will have no difficulty devising myriad obvious improvements upon and variants of the invention, without departing from the invention; all such obvious improvements and variants are intended to be encompassed by the claims which follow.

Claims

1. A method for use with a capacitor and with a battery having a first level of function at a first temperature and having a second level of function at a second temperature lower than the first temperature, the second level of function being lower than the first level of function, the method comprising the steps of:

at a time when the battery is at the second temperature, commencing cycling of current from the battery to the capacitor and from the capacitor to the battery until the battery's temperature reaches the first temperature;

wherein the cycling of current comprises the steps, carried out in alternation, of:

- during a first interval of at least one-tenth of a second in duration, passing current from the battery to the capacitor; and
- during a second interval after the first interval, the second interval being at least one-tenth of a second in duration, passing current from the capacitor to the battery;

whereby the passage of current through the battery warms the battery.

2. The method of claim 1 wherein each of the first interval and the second interval has a duration of at least one second.

3. The method of claim 2 wherein each of the first interval and the second interval has a duration of at least two seconds.

4. The method of claim 1 wherein the capacitor is an ultracapacitor.

5. The method of claim 1 wherein the level of current employed in the cycling is at a first level when the battery is at the second temperature, and wherein the level of current employed in the cycling is greater when the battery is warmer than the second temperature.

6. The method of claim 1 wherein the cycling of current between the battery and the capacitor is discontinued in the event of the capacitor being at or below a third temperature.

7. A system comprising:

a capacitor;

a battery having a first level of function at a first temperature and having a second level of function at a second temperature lower than the first temperature, the second level of function being lower than the first level of function; and

cycling means, the cycling means responsive to the battery being at the second temperature for commencing cycling of current from the battery to the capacitor and from the capacitor to the battery until the battery's temperature reaches the first temperature;

wherein the cycling of current comprises the steps, carried out in alternation, of:

> during a first interval of at least one-tenth of a second in duration, passing current from the battery to the capacitor; and
> during a second interval after the first interval, the second interval being at least one-tenth of a second in duration, passing current from the capacitor to the battery.

8. The system of claim 7 wherein each of the first interval and the second interval has a duration of at least one second.

9. The system of claim 8 wherein each of the first interval and the second interval has a duration of at least two seconds.

10. The system of claim 7 wherein the capacitor is an ultracapacitor.

11. The system of claim 7 wherein the level of current employed in the cycling is at a first level when the battery is at the second temperature, and wherein the level of current employed in the cycling is greater when the battery is warmer than the second temperature.

12. The system of claim 7 wherein the cycling means is responsive to the capacitor being at or below a third temperature for discontinuing cycling of current between the battery and the capacitor.

13. Apparatus for use with a capacitor and with a battery having a first level of function at a first temperature and having a second level of function at a second temperature lower than the first temperature, the second level of function being lower than the first level of function;

the apparatus comprising cycling means disposed for interconnection with the capacitor and with the battery, the cycling means responsive to the battery being at the second temperature for commencing cycling of current from the battery to the capacitor and from the capacitor to the battery until the battery's temperature reaches the first temperature;

wherein the cycling of current comprises the steps, carried out in alternation, of:

> during a first interval of at least one-tenth of a second in duration, passing current from the battery to the capacitor; and
> during a second interval after the first interval, the second interval being at least one-tenth of a second in duration, passing current from the capacitor to the battery.

14. The system of claim 13 wherein each of the first interval and the second interval has a duration of at least one second.

15. The system of claim 14 wherein each of the first interval and the second interval has a duration of at least two seconds.

16. The apparatus of claim 13 wherein the level of current employed in the cycling is at a first level when the battery is at the second temperature, and wherein the level of current employed in the cycling is greater when the battery is warmer than the second temperature.

17. The apparatus of claim 13 wherein the cycling means is responsive to the capacitor being at or below a third temperature for discontinuing cycling of current between the battery and the capacitor.

FIG. 1

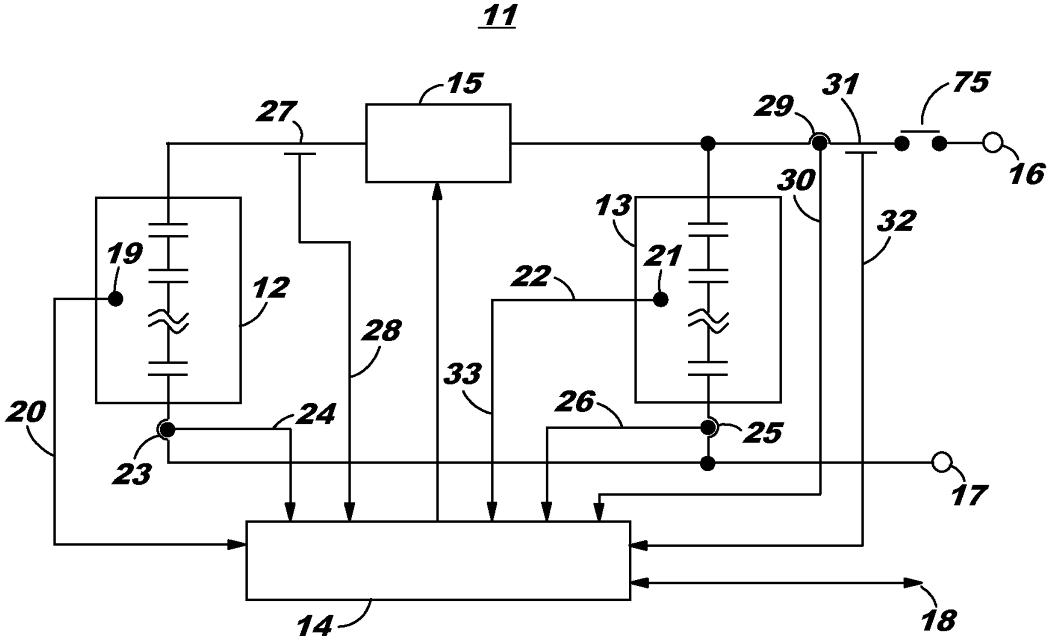

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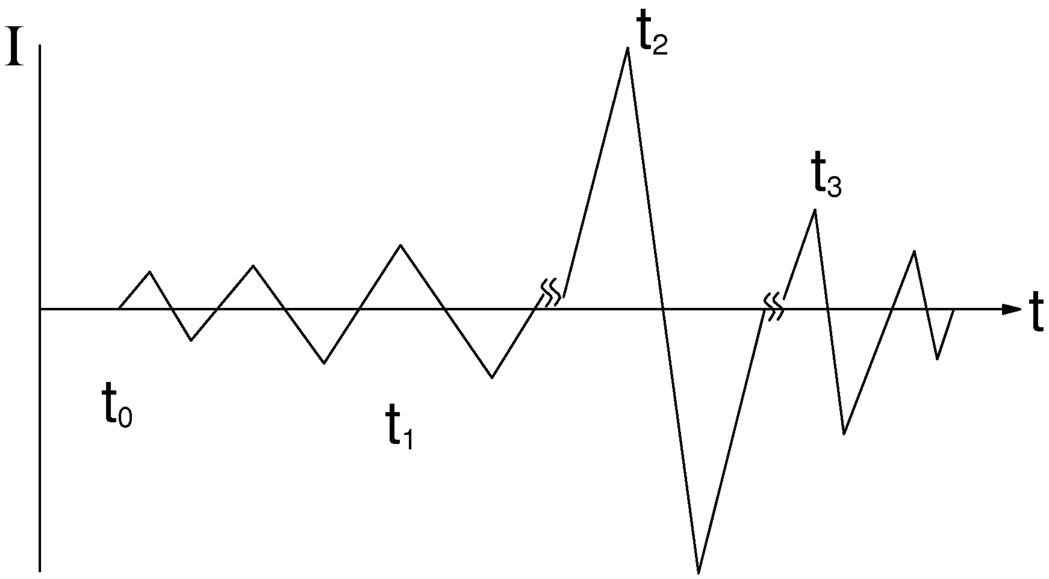
FIG. 2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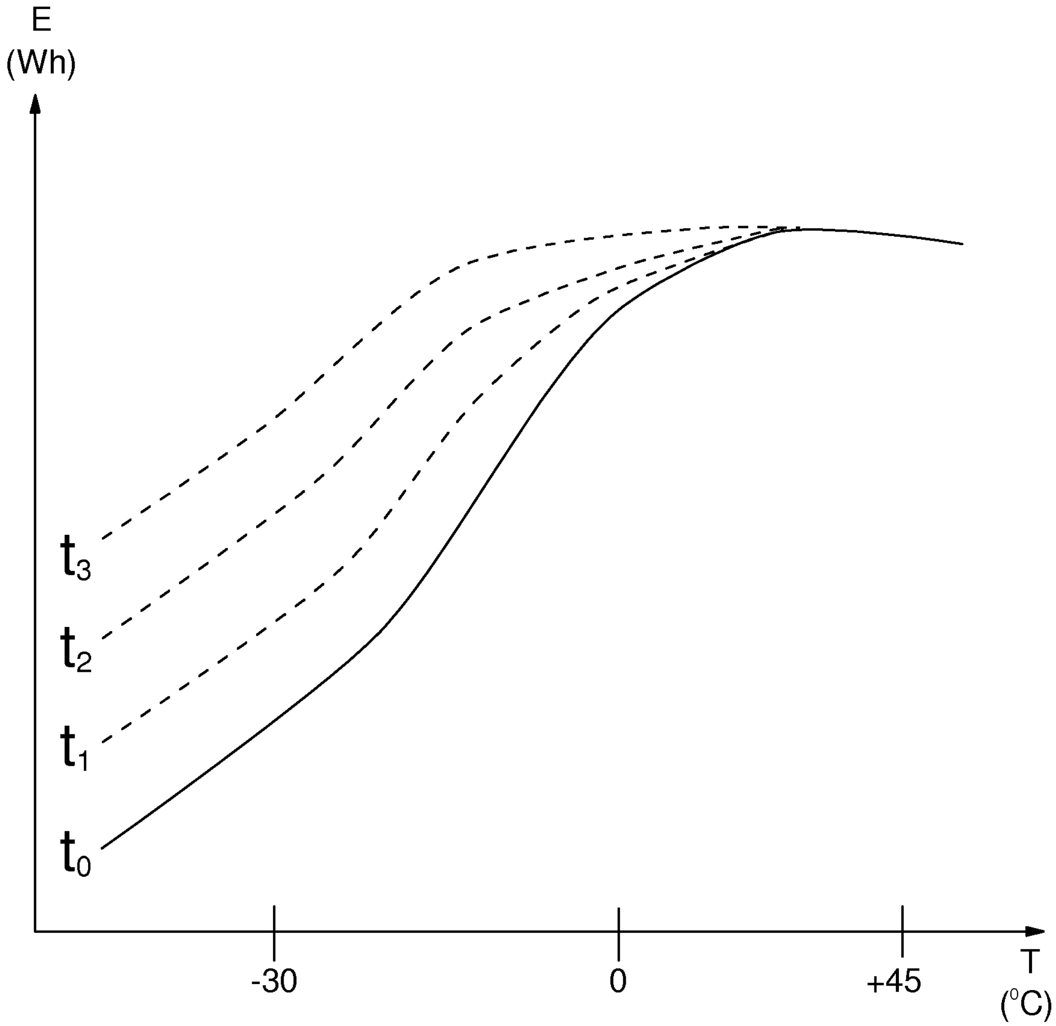

FIG. 4

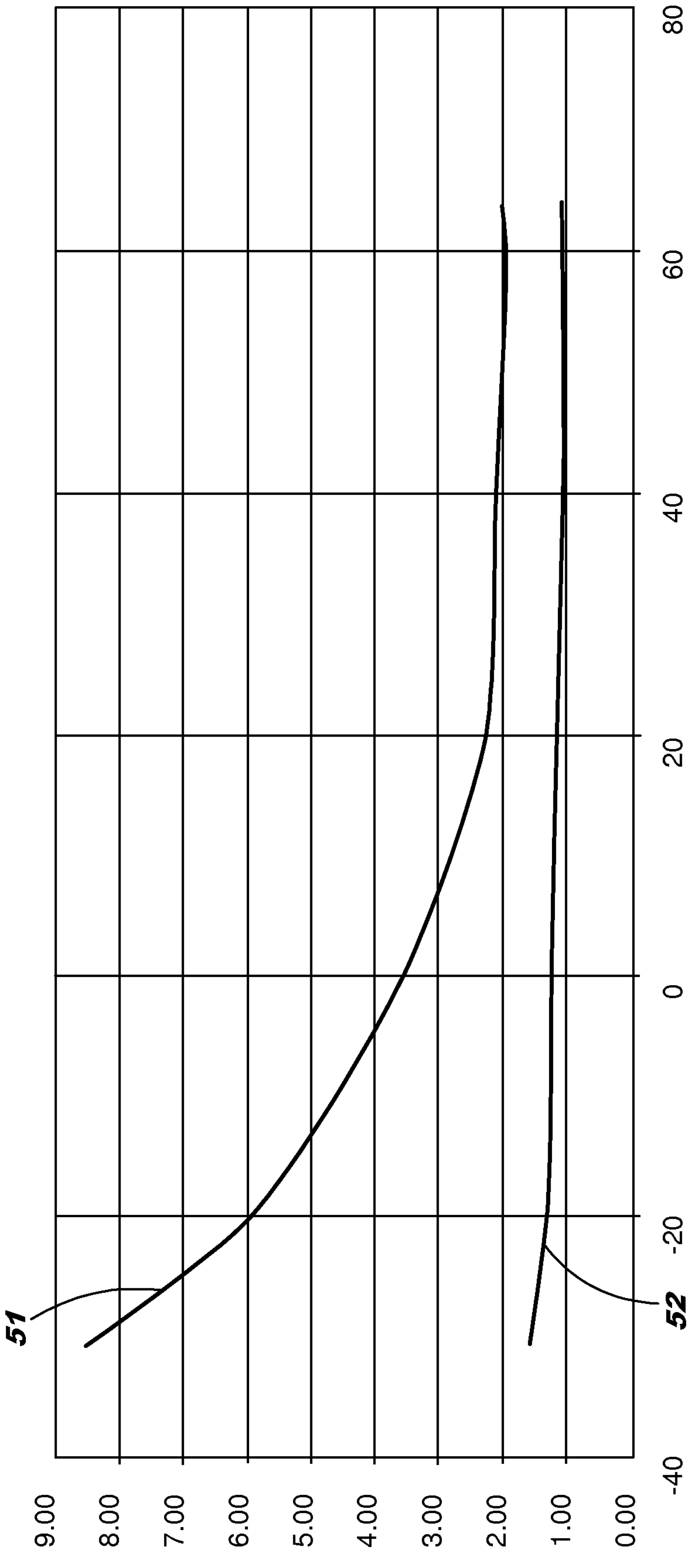

FIG. 5

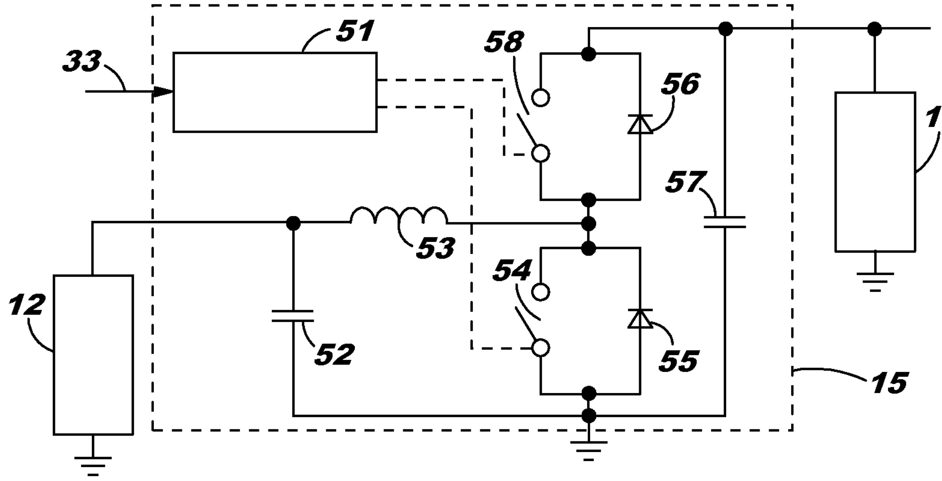
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FIG. 6

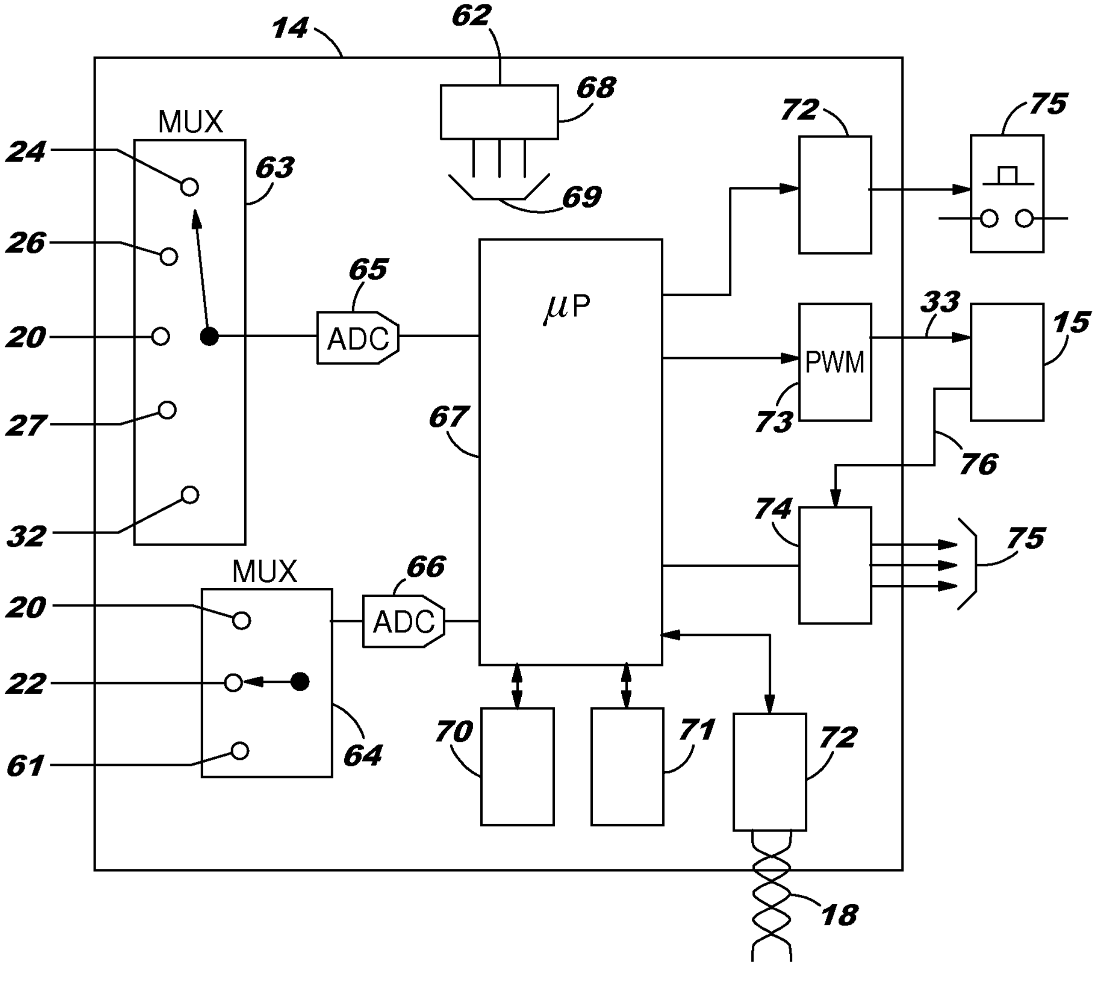
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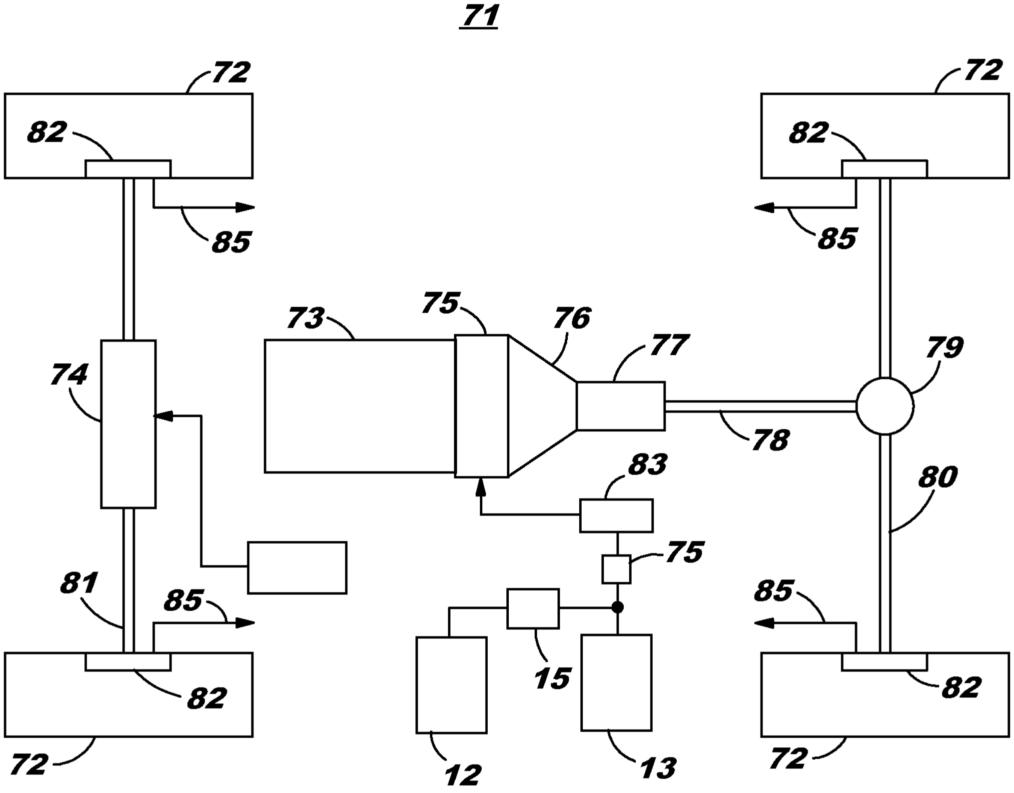
FIG. 7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INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2011/050395

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01M10/44 H01M10/50

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2003 274565 A (NISSAN MOTOR) 26 September 2003 (2003-09-26) abstract; figures 5,6 -----	1-17
A	JP 2008 035581 A (TOYOTA MOTOR CORP) 14 February 2008 (2008-02-14) cited in the application abstract; figures 1,6,10-13 paragraphs [0012], [0051], [0129] -----	1-17
A	US 6 072 301 A (ASHTIANI CYRUS N [US] ET AL) 6 June 2000 (2000-06-06) cited in the application the whole document ----- -/--	1-17

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
19 April 2011	28/04/2011

Name and mailing address of the ISA/

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Chmela, Emil

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2011/050395

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 990 661 A (ASHTIANI CYRUS N [US] ET AL) 23 November 1999 (1999-11-23) cited in the application abstract; figures 1,2 column 3, lines 13-40 -----	1-17

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2011/050395

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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